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SMOKE PLUME BEHAVIOR – WHAT THE DATA SAY

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1. INTRODUCTION

A comprehensive smoke project, now ongoing for four years, is designed in part to investigate plume behavior from Southern prescribed burns with respect to atmospheric stability and to document ground-level smoke concentrations with PM_{2.5} data from a network of samplers specially constructed for the project. Project management goals are to find ways to increase the number of burn days and/or the number of acres burned on a given day while remaining within air quality guidelines. Project scientific goals are to advance knowledge on how smoke from prescribed burns is distributed in the atmosphere as functions of weather and firing method.

The Smoke Project collects two diverse data sets. First, ground-level measurements of daily (22 hr average) of PM_{2.5} are taken with up to 20 samplers spaced in a fan-shaped network extending downwind from the burn site for distances up to 2.5 miles (4.0 km). Second, airborne temperature soundings are taken in close proximity to smoke plumes and photographic documentation of plume behavior is done.

2. MATERIALS AND METHODS

a) Ground-Based Measurements

Time-integrated particulate data analyzed by gravimetric methods were collected by SKC pumps drawing air at a rate of 4.0 L/min through a BGI KTL cyclone and SKC Air Check 2000 pumps drawing air at a rate of 1.5 L/min through a BGI Triplex cyclone (SKC, Waltham, MA; BGI, Waltham, MA). Both cyclone types used 37 mm Teflo filters to which the particles adhered (Pall Co.). The cyclones were hung approximately 1.5 meters off the ground in a fan-shaped network that spread out downwind from the burn site. The locations of the pumps was quasi-random but was restricted by the network of roads at

the Savannah River Site. Two pumps, designated as base-line reference pumps were set up wind from the burn site to provide measurements of the background PM in the area. All pumps were set to run for 22 hours (10 am-8am) in order to catch smoke produced during the active burning and smoldering phases. Measurements were terminated at 8am to give time for filters to be exchanged and pumps relocated in the event of a new burn on the following day.

In preparation for gravimetric analysis, filters were stored under partially controlled climate conditions ($20.6 \pm 1.4^{\circ}\text{C}$) for at least 48 hours prior to pre-weighing and for at least 48 hours prior to initial post-weighing. Filters were weighed using the Cahn C-35 microbalance with a sensitivity of $\pm 1 \mu\text{g}$ following the EPA's Quality Assurance Guidance Document (i). Air densities during weighing sessions, nominal densities of calibration masses, and a filter density were used to adjust the balance readings for the buoyancy effect of air. For each filter, two pre-weights and two post-weights were performed. The sample volume was obtained by multiplying sampling time and the average of the on flow and off flow rates. PM_{2.5} concentration was calculated as the weight difference between the filter pre-weights and the post-weights, after adjusting for field blank, divided by the sample volume.

b) Airborne Measurements

The experimental design calls for an aircraft equipped with instruments to record air temperature and the location and altitude of the aircraft in close proximity of a smoke plume. The vertical distribution of temperature within the layers of air containing the smoke can be measured by periodically flying spiral ascent and descent patterns from several hundred meters above ground to altitudes 300 m above the top of the plume. These temperature "soundings" can be analyzed to

determine the altitude of the top of the mixed layer.

The experimental design also calls for extensive photographic documentation of the plume. A digital camera was equipped with a clock for recording the time to the nearest minute each photograph is taken. One key task is to photograph the top of the plume in line with the horizon – a measure of the altitude of the top of the plume.

Through its recorded time, each photograph can be georeferenced to the location and altitude of the aircraft. Thus, with the photographic data giving reference to the visual top of the plume and the temperature data giving information on the top of the mixed layer, the depth of smoke penetration into the free atmosphere above the mixed layer can be calculated.

Four copper-constantan duplex insulated thermocouples were attached to the footpad on the wheel strut of a Cessna 182 aircraft. Two were fabricated of coarse wire (24 gauge – 0.05 cm) and two were fabricated of fine wire (36 gauge – 0.013 cm). Leads were run from these sensors to a Campbell data recorder located in the baggage compartment of the aircraft. A portable GPS unit with antenna attached to the rear overhead window of the aircraft provided location and altitude.

3. RESULTS

Ground-Based Measurements

Figure 1 shows locations of PM_{2.5} samplers and 22 hr average PM_{2.5} concentration for a 120 acre burn. Figure 2 shows the same for a 2745 acre burn. Both figures include wind rose diagrams for the afternoon (active flaming stage) and the nighttime (smoldering stage) of the burns. Two salient points regarding these figures are: First, the expected gradual decline in PM concentrations with distance from the burns did not occur. Relatively large concentrations were found near the boundary of the burn but elsewhere, concentrations were at or slightly above background concentrations. Second, the magnitudes of PM concentrations between Figure 1 and Figure 2 are approximately the same even though the burn in Figure 2 was 23 times larger than the burn in Figure 1. The expected much larger concentrations extending much farther down wind for the burn in Figure 2 did not occur.

Airborne Measurements

Two prescribed burns totaling approximately 1200 acres were conducted at the Oconee National Forest and at the Piedmont National Wildlife Refuge located in central Georgia on 06 March 2002. The weather was clear with steady winds from the south at approximately 4 m sec⁻¹.

Figure 3 shows the well developed smoke plume at 1419 LST looking Southwest toward the burn site. The top of the plume has been lined with the horizon to estimate the plume top height. The flattened top of the plume gives the appearance that the plume has grown to just fill the depth of the mixed layer.

Figure 4 shows one of several temperature soundings taken during the flight. The aircraft descended to an altitude of 400 m msl (150 m agl) then performed a steady spiral climb to 2300 m msl. After maintaining altitude for several minutes, the aircraft descended back to 400 m msl. If the slope of the temperature profile roughly parallels the slope of the dashed line (representing neutral stability), the temperature profile is representative of that in the mixed layer. The temperature profiles for both the ascent and descent legs of the sounding flight both satisfy this condition below 1500 m. From 1500 m to 2300 m, the sounding is representative of the stability within the free atmosphere above the mixed layer. The top of the smoke plume is identified by the dashed line at 2200 m. The gray area identifies error bounds in estimating the altitude of the top of the plume from the photograph. The error is defined as the change in altitude of the aircraft over the one minute spanning the time of the photograph. The dashed line box from 1500 m to 2200 m identifies the depth of the free atmosphere above the mixed layer that contains smoke. Roughly 700 m (37 percent) of a plume 1900 m deep lies above the mixed layer.

4. DISCUSSION

The results to date from the Smoke Project at the Savannah River Site in South Carolina are contrary to expectations based on simple indices, such as the ventilation index and screening models such as VSMOKE. Prescribed fire practitioners are able to "engineer" their burns to place smoke into the free atmosphere above the mixed layer. This engineering is most effective for

the larger burns which release the greatest amounts of fine particulate matter into the atmosphere. The outcome is that smoke concentrations in the vicinity of the burns (within several miles) are far less than expected. The risks are that large amounts of smoke are injected into layers of the atmosphere, often with wind speeds and

directions that differ from those in the mixed layer, and this smoke is carried large distances in high concentration to unexpected destinations. There have been noted instances when weather conditions have returned this smoke back to the mixed layer and thence to the ground.

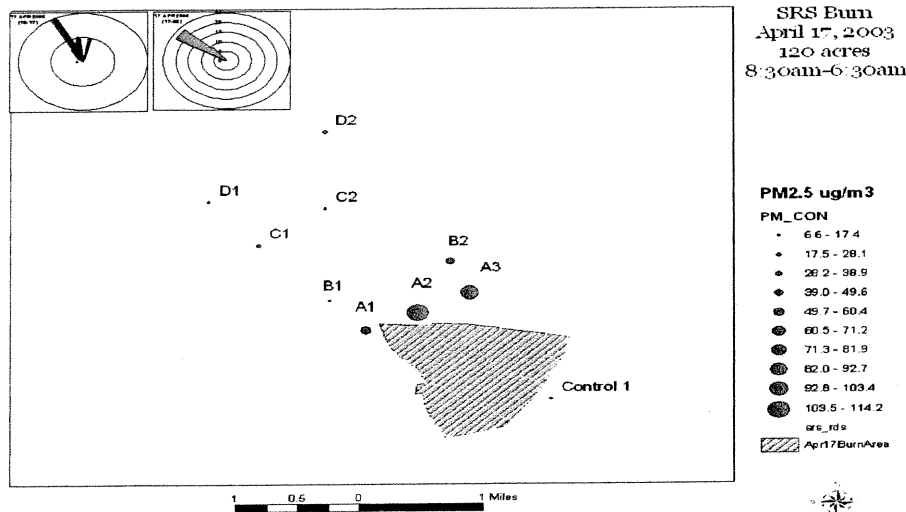


Figure 1. Distribution of samplers and PM_{2.5} concentration downwind from a 120 acre prescribed burn.

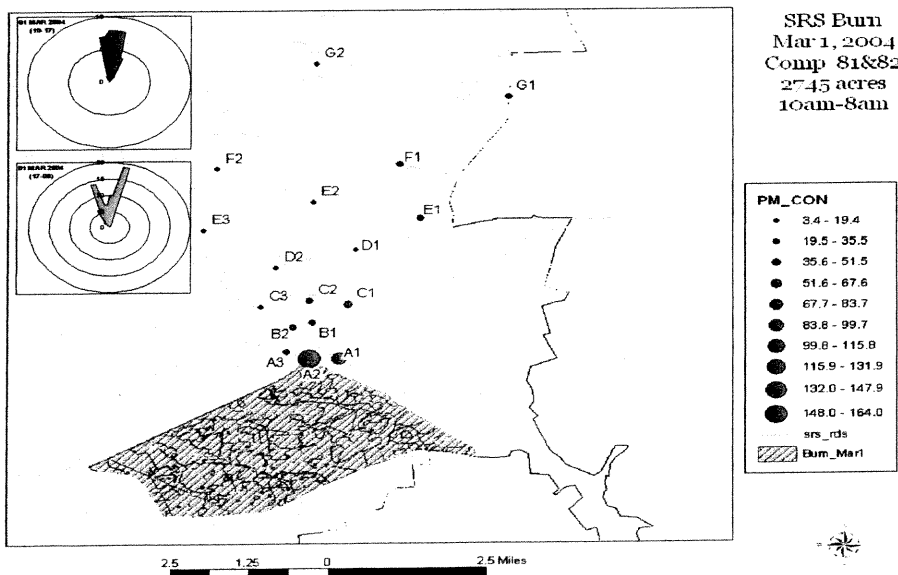


Figure 2. Distribution of samplers and PM_{2.5} concentration downwind from a 2745 acre prescribed burn.



Figure 3. The smoke plume at 1419 LST during the second leg of the flight.

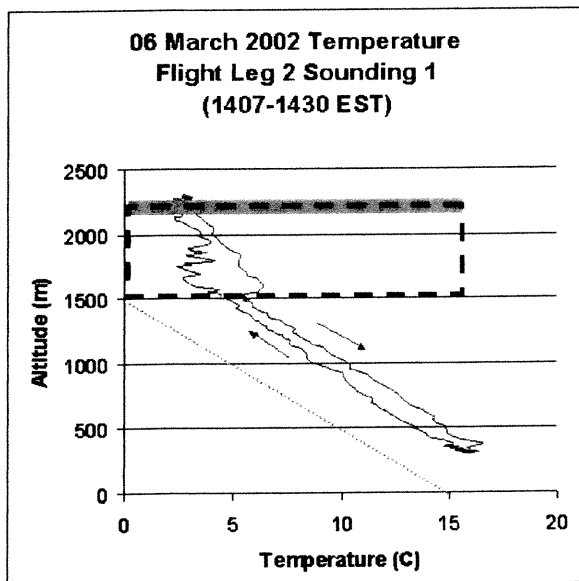


Figure 4. The complete sounding for Flight Leg 1. The dashed line gives the temperature profile for neutral mixing. The top of the smoke plume is identified by the dashed line at 2000 m. The gray area identifies error bounds in the altitude of the top of the smoke plume. The dashed line box identifies depth of the atmosphere above the mixed layer that contains smoke.

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